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Star Formation in Dwarf Galaxies: Life in a Rough Neighborhood

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Star Formation in Dwarf Galaxies: Life in a Rough Neighborhood

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Abstract. Star formation within dwarf galaxies is governed by several factors. Many of these factors are external, including ram-pressure stripping, tidal stripping, and heating by external UV radiation. The latter, in particular, may prevent star formation in the smallest systems. Internal factors include negative feedback in the form of UV radiation, winds and supernovae from massive stars. These act to reduce the star formation efficiency within dwarf systems, which may, in turn, solve several theoretical and observational problems associated with galaxy formation. In this contribution, we discuss our recent work being done to examine the importance of the many factors in the evolution of dwarf galaxies.

1. Introduction

In the favored cosmological models, in which the matter is dominated by cold dark matter, galaxy formation occurs in a hierarchical fashion. Dwarf systems are the first to form, while more massive galaxies form via the merger and accretion of smaller systems (see, eg. Blumenthal et al. 1984; Navarro, Frenk, & White 1997; Klypin, Nolthenius, & Primack 1997). This picture has had many successes, but some outstanding problems remain.

1) The Over-cooling Problem: At high redshifts, the high densities and pressures make it relatively easy for the first objects to form to cool and form stars. It would seem likely, therefore, that the first dwarf systems would rapidly cool, contract, and undergo efficient bursts of star formation. The remaining, highly condensed gas clouds would be required to lose a great deal of angular momentum via dynamical friction before they could merge to form larger systems. The resulting large galaxies would have massive, extended, old haloes, with highly concentrated regions of younger stars, very different from the galaxies that we see today (White, & Rees 1978; Navarro & Benz 1991; Navarro & White 1994).

2) The Missing Dwarf Problem: The high phase space densities of the first dwarf systems to form implies that many of their cores should survive mergers (Moore et al. 1999; Klypin et al. 1999). Observationally, no unambiguous identification of a surviving core of a dwarf system has been made, although such an origin has been proposed for ω Cen (eg. Norris, Freeman, & Mighell 1996).

3) The Overheating Problem: The formation of AGN in the early universe led to a strong cosmic UV background (Haardt & Madau 1996). Some studies indicate that the background UV was sufficient to ionize many dwarf systems right up to the current epoch, which should prevent any star formation within those systems (Kepner, Babul, & Spergel 1997). Observationally, however, almost all dwarf galaxies show continuous star formation, dating from the earliest epochs until relatively recent times, or even ongoing, in the case of dwarf Irregular (dI) galaxies (Grebel 1997; Grebel & Stetson 1998).

4) The Missing Gas Problem: As discussed above, almost all dwarf systems have undergone extended star formation histories, including dwarf elliptical (dE) and dwarf spheroidal (dSph) systems. Those latter systems, however, are gas-poor (Knapp, Kerr & Bowers 1978; Mould et al. 1990; Bowen et al 1997; Carignan et al. 1998). The mechanism by which gas may be removed relatively rapidly remains undetermined.

The first two problems may both be solved by internal feedback. Ultraviolet radiation, stellar winds, and supernova input energy and momentum into the gas, reducing the star formation efficiency. They shall also act to prevent cooling and contraction of the dwarf systems, allowing mergers at earlier times, requiring less loss of angular momentum. Feedback from star formation has been included in cosmological models in an *ad hoc* fashion (Weil, Eke & Efstathiou 1998; Navarro & Steinmetz 1997; Sommer-Larsen, Gelato & Vedel 1999). We wish to place that solution on a more quantitative basis.

Other factors may aid in solving the third and fourth problems. Previous models assumed very small baryonic fractions for the smallest dwarf systems, making extremely easy for them to be ionized by the background UV radiation. Dynamical factors may also act to enhance their ability to recombine, cool, and form stars. The final problem may be solved by tidal stripping, in combination with ionization.

In addition to examining solutions to the above problems, we wish to examine the interplay of the various factors that affect star formation, to potentially explain the rich variety of star formation histories observed within dwarf systems (Grebel 1997; Grebel & Stetson 1998; Mateo 1998). The same factors which goverened star formation at early times within dwarf galaxies continue to affect star formation today. In addition to shedding light upon the early star formation history of the universe, dwarf galaxies may therefore serve as valuable laboratories for studying the current process of star formation.

2. Internal feedback and external heating

2.1. Our models

We have examined the effects of external UV heating, feedback from star formation, and external perturbations using a one-dimensional Lagrangian hydrodynamics code (Dong, Lin, & Murray 2003). The gas evolves within a dark matter potential, having a form found by Burkert (1995) to be a good fit to the potentials of a wide range of dwarf galaxies. The gas is exposed to UV both externally from the cosmic background and internally from massive stars. Radiation transport is handled using a "Strömgren shell" approximation. In regions which are fully ionized, the gas temperature is set to 15,000 K, characteristic of low metallicity, ionized gas. In regions which are largely or completely shielded from UV heating, the gas is allowed to radiatively cool, and star formation may occur.

The conversion of gas to stars has a maximum rate, which we set to be a fraction of the gas density, ρ, divided by its free-fall time, τ_{ff}. Several factors may, however reduce the efficiency from its maximum value. If the Jeans mass exceeds 100 $_{\odot}$, then the timescale over which the gas contracts to form stars is much less than the subsequent timescale for the stars to evolve onto the main sequence. The first stars to form shall, therefore, re-heat the surrounding gas, preventing further star formation. In any other situation where τ_{ff} exceeds the typical pre-main sequence lifetime of a massive star, τ_{pms}, the same situation shall occur. Finally, if the radius of a Jeans mass of gas exceeds the Roche radius of that gas within the potential of the dwarf system, the gas shall be unable to contract to form stars. If any of these criteria are met in the models, the star formation efficiency is rapidly reduced from its maximum value.

Once gas has been converted to stars, feedback occurs via three channels. Ultraviolet radiation from the stars may ionize and heat the gas, and is included assuming a Miller-Scalo IMF. Stellar winds and supernovae add momentum to the gas, and their contribution is included in a "kinetic pressure" term in the equation of motion. The feedback does not occur immediately, but is delayed by different times. The UV heating and winds are delayed by a time $\tau_{ff} + \tau_{pms}$, while the supernova input is delayed by an additional τ_*, the typical lifetime of massive stars.

Some of the models are also subjected to an initial, inwardly-directed "Hubble flow" (magnitude of the velocity increasing linearly with radius). Such perturbations are designed to approximate the effects of either inflow of accreted gas, or collisions with neighboring systems.

2.2. Results

In contrast to earlier work, we find that many dwarf systems are able to form stars, even at high redshifts where the background UV is most intense. The primary difference with the earlier work is that our models adopt baryonic-to-dark matter ratios close to the cosmic value, assuming that the dark and baryonic matter remain coupled at all times.

In the low mass models, corresponding to most dSph's, star formation is extremely inefficient, and typically occurs in a single, early burst. Feedback from the stars formed in the burst expands the remaining gas sufficiently for it to be

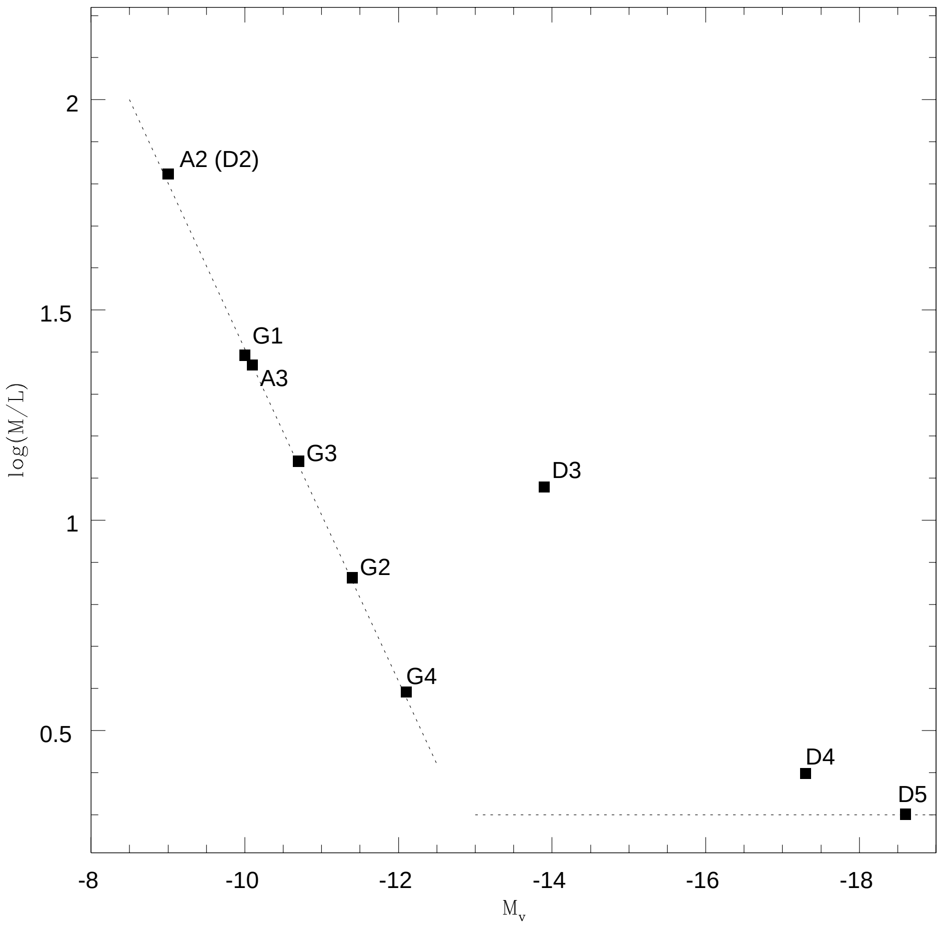

Figure 1. Mass-to-light ratios derived for small model galaxies, plotted as a function of their absolute magnitudes. The models with $M_V > -14$ all have similar dark matter masses, and differ primarily in the strength and timing of the internal feedback from star formation.

completely ionized by the external UV radiation, terminating star formation. The lowest mass models are completely ionized at all times by the external UV. In order for there to be any star formation within those systems, or ongoing star formation within somewhat larger systems requires perturbations to the density sufficient to allow some self-shielding of the gas.

More massive models, corresponding to the most massive dSph's, dE's and dIrr's, undergo continuous star formation. Depending upon the timing and efficiency of the feedback, the star formation may become episodic. That typically requires either that the feedback be inefficient or delayed by a time comparable to the dynamical timescale of the galaxy. In either case, the gas is then able to evolve significantly before feedback is able to strongly affect it, leading to oscillatory behavior.

A striking result of the models comes when we plot the mass-to-light ratio computed from the models as a function of their absolute magnitude, as shown in Figure 1. That figure compares remarkably with observed results for local dSph's (Mateo et al. 1998, see their Figure 7). All of the models shown have very similar dark matter haloes, and differ primarily in the timing and efficiency of the feedback. Such sensitivity of the results to changes in the feedback parameters implies that these small systems are at the very edge of being able to form stars. Many, indeed, may have been unable to form stars at all (see below).

3. Tidal stripping

It might be expected that at least some of the gas that has been ionized by the UV background would eventually be able to cool and form stars when the external UV flux decreased sufficiently in intensity. A dwarf galaxy which is orbiting within the potential of either a cluster or a nearby massive galaxy, however, is subject to tidal stripping (Murray, Dong, & Lin 2003). Near the L_1 and L_2 points, where the potential has a saddle shape, the scale height of the gas becomes infinite, and gas shall flow outwards at the sound speed. The gas lost to is replaced on a sound crossing time, as the system attempts to re-adjust to hydrostatic equilibrium. The result is continuous mass loss, as shown in Figure 2.

The significance of the mass loss depends critically upon the ratio $c_s/\phi_0^{1/2}$, where c_s is the sound speed of the gas, and ϕ_0 is the depth of the potential of the dwarf galaxy, measured from the center to the Lagrange points. We find from analytic, and both one- and three-dimensional numerical models that, if $c_s/\phi_0^{1/2} \gtrsim 0.1$, then essentially all of the gas may be lost from the galaxy within 1 Gyr. The stellar velocity dispersions of most dSph's are less than 10 km s^{-1}, implying that, for ionized gas, $c_s \sim \phi_0^{1/2}$. Unless such small systems are in relative isolation, therefore, their gas may be rapidly lost to them once it becomes completely ionized either by internal or external UV radiation. Star formation may, therefore, be a self-terminating process within small dSph's. In the smallest systems, which are initially completely ionized by the external UV flux, star formation may be prevented entirely, leading to the formation of starless, dark matter clumps orbiting within the haloes of massive galaxies. Such

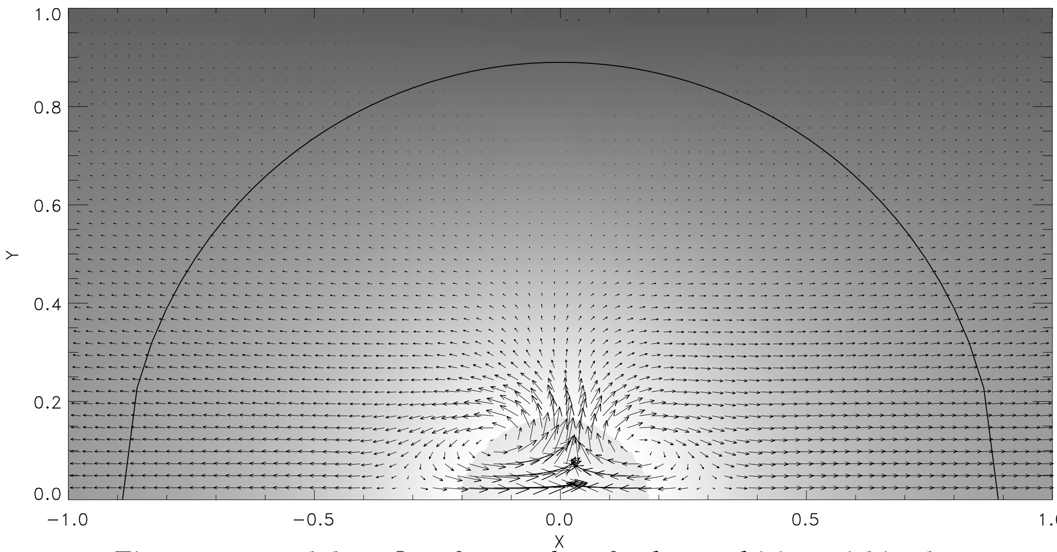

Figure 2. Tidal outflow from a dwarf galaxy orbiting within the potential of a Milky-Way sized galaxy. Arrows indicating mass flux, $\rho\mathbf{v}$, are shown superimposed upon density grayscale. Focussing of the flow near the L_1 and L_2 points is apparent. The radius of the circle is equal to the distance of the Lagrange points from the center of the dwarf galaxy.

substructure may have been seen in recent gravitational lensing observations (Metcalf 2002; Metcalf & Zhao 2002).

The gas lost to tidal outflow is not, however, necessarily permanently lost to the system. The gas which is lost flows outwards at the sound speed, which is much smaller than the orbital speed of the dwarf around a parent galaxy, and shall therefore follow an orbit around the massive galaxy close to that of the dwarf system. As the dwarf approaches the apocenter of its orbit, nearby orbits converge, and the tidal radius of the dwarf increases in size. Both factors combine to possibly lead to re-accretion of gas, potentially triggering self-shielding and star formation. In some systems, therefore, star formation may be episodic, with a periodicity related to the orbital period of the dwarf around the massive parent galaxy.

4. Discussion

Our models are beginning to place some of the *ad hoc* assumptions of some cosmological models onto a more quantitative, physical footing. As required by those models, a low level of star formation is found to be sufficient, via negative feedback, to prevent runaway star formation, and maintain the system at a sufficient size that merging can occur without the loss of too much angular momentum.

If anything, the feedback may be *too* effective, and star formation within the smallest dwarf systems is found to be extremely inefficient in our models. In order to have ongoing star formation requires external perturbations, such as might result from collisions, accretion, or possibly ram pressure. Our models indicate that the first two processes may lead to bursts of star formation, and we shall examine the effects of ram pressure in upcoming work.

Tidal stripping is extremely effective at removing ionized gas from low mass systems. Because the gas is lost at low speeds relative to the dwarf system, it shall follow a similar orbit around the parent galaxy. Re-accretion near the apocenter of the orbit may lead to episodic star formation within the dwarf, but after a few orbits the gas shall be lost to the system. Tidal loss may therefore explain the absence of gas in many dwarfs that have experienced extended star formation histories. For most of their history, the gas density was sufficient that it could be self-shielded from the external UV flux. As the gas was depleted via star formation and tidal stripping, however, the density eventually dropped sufficiently for it to be completely ionized. Star formation was then terminated and the remaining gas eventually lost.

For very low mass systems, star formation is prevented by the external UV radiation from the earliest times onward. Tidal stripping of the gas then leads to the formation of starless, dark matter clumps orbiting within the halo of massive galaxies, such as are indicated in recent gravitational lensing observations.

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